Distinguishing between $w < -1$ Dark Energy Models

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Abstract. Recent data and new data analysis methods show that most probably the parameter w in the equation of state of the dark energy is smaller than -1 at low redshifts. We briefly review some of the models with such a property and without violating null energy condition. We investigate the difference between the observables and predictions of these models, and how they can be explored to single out or constrain the origin of dark energy and its properties.

Keywords: Dark energy, Dark matter, Cosmology, Early universe

Understanding the nature of dark energy is one of the biggest challenges in present cosmology and particle physics. In order to achieve this goal, the measurement of the cosmological evolution of the dark energy, parameters of the candidate models, and their origin and relation with other contents of the Universe are of extreme importance. This also means that the way we model the data and extract parameters affects our interpretation of what is the dark energy and how it evolves.

At present all the determination of dark energy parameters is based on the simplest extension of the LCDM. The energy content of the Universe is usually considered to be composed of 3 components: cold visible and dark matter, hot matter, and a dark energy component with a perfect fluid equation of state:

$$\frac{H^2(z)}{H_0^2} = \frac{\rho(z)}{\rho_0} = \Omega_m(1+z)^3 + \Omega_{hot}(1+z)^4 + \Omega_{de}(1+z)^{3\gamma(z)} \tag{1}$$

When $\gamma(z)$ does not depend on redshift, $\gamma = w + 1$, and $w \equiv P/\rho$. We note that in this definition no interaction between various components is included. Although observations of the CMB anisotropy shows that the non-gravitational interaction between the hot matter - mainly CMB - and dark and baryonic matter is very small, the constraints on the non-gravitational interaction between dark components are not very strong[1].

Using 1 for fitting data from CMB, LSS, and supernovae, the estimations of recent measurements are summarized in Fig.1. Many of these estimations relay on multiple type of data to remove the degeneracy between cosmological parameters.

Therefore in this sense not all of them are independent. Nonetheless, if we assume that the difference in their estimation is statistical, the best estimation of w would be the weighted average of all the measurements. What one obtains in this way is $w = -1.056 \pm 0.023$ at 2σ level. This value as well as the individual measurements are all very close to the critical value $w = -1$ (a cosmological constant). Nevertheless, the best estimation and most of the measurements are consistent with $w \lesssim -1$. In the most simplistic view of the data we can say that the deviation from a cosmological constant is
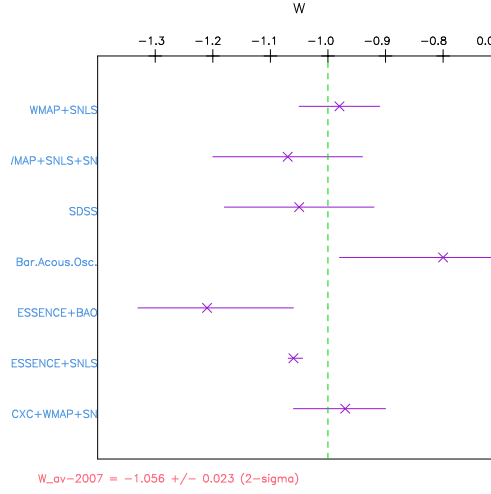
FIGURE 1. Recent estimations of *w* and their weighted average.

due to the errors. However, considering the best estimation mentioned above, even at 2σ level $w < -1$. This can be the evidence of a much richer physics behind the dark energy than just a putative cosmological constant.

Evidently just one number is not enough to decide about the nature of such a complex entity as the dark energy. There have been a number of attempts to estimate the redshift evolution of *w*. Although present data is not ideal for this purpose, the minimal conclusion is that it does not significantly vary up to $z \sim 1$[2]. Here we want also to mention very briefly the issue of the techniques usually employed to determine the equation of state of the dark energy from data. In most data sets one has to fit a large number of parameters including *w* or its redshift expansion parameters together. Although this method is acceptable for quantities that their exact value is not crucial for their physics such as Ω_{dm} - at least not at our present level of knowledge e- the degeneracy in fit results can be very important for parameters close to a critical value such as *w*. A method based on geometrical properties of $d\rho/dz$ is suggested [3] which in one hand permits to directly measure the sign of *w* and its redshift dependence. On the other hand, up to certain limits its results are less affected by the uncertainty in prior parameters such as H_0 and Ω_m. Application of this method to the publicly available SN type I data shows that $w < -1$ at least up to $z \sim 0.5$ and its variation, if exists, is very small.

The main argument - or rather we can call it "fear" - against $w < -1$ is that it violates the weak energy condition i.e. $P_{de} + \rho_{de} \geqslant 0$. However, we should remember that this condition is written for a perfect fluid without interaction. If the interaction between various components, in particular with the dark energy, is taken into account the form of null energy condition would be much more complex and eventually *w* can be less than -1 without violation of any fundamental law of physics. In this case the evolution of total density can be written as:

$$\frac{\rho(z)}{\rho_0} = \Omega_m(1+z)^3 + \Omega_{hot}(1+z)^4 + \Omega_{de}(1+z)^{3\gamma(z)} + g^2 f(\Omega_m, \Omega_{hot}, \Omega_{de}, z) \quad (2)$$

where *f* is an unknown function and depends on the dark sector model. It is possible

to show that for a number of models in which dark matter and dark energy interact with each other or are not an ideal fluid, *the effective w* when 1 is used to analyze the data in place of 2, is smaller than -1. Here we mention a few examples of these models. The simplest example is a decaying dark matter with cosmological constant as dark energy[4]. The next one is a decaying dark matter with a very small branching ratio to a light, axion-like scalar[5, 6]. The condensation of this field plays the role of a quintessence field with an evolution very similar to a cosmological constant from very early times after formation of the meta-stable dark matter. Finally the last example we mention here is a stable dark matter interacting with a quintessence field as dark energy[7]. Many other examples can be found, but at least some of them imply a violation of equivalence principal or cosmological variation of particle masses and couplings which are strongly constrained by the non-observation of density dependent effects of dark energy at cosmological distances.

How can we distinguish between these models ? This task is specially more difficult in the situation where dark energy does not strongly vary with redshift. But even if it has some variation, it is very difficult to conclude the nature of the underlaying model just from a couple of parameters that determine its variation. We need additional observables more closely related to the field theoretical aspects of the models. At present level of our knowledge about the physics beyond the Standard Model, it is very difficult to place the dark energy field - quintessence scalar - in the zoo of particles. Nonetheless, it is possible to guess some of the possible observables. For instance, if dark matter has a non-gravitational interaction with dark energy condensate, we expect that *dark energy particles* are released from the condensate. As they are expected to be very light, they should make a hot dark background of non-SM nature. This process is very similar to the scattering from a Bose-Einstein condensate[8]. The cosmological density of this hot component and its evolution depends on the type and strength of the interaction. These are unknown, but from constraints on the clustering of the dark energy we expect that the coupling must be very small, and therefore the density of the corresponding hot matter should be small too - probably less than CMB, nonetheless the observation of such a component can significantly help to understand the origin of dark energy. On the other hand, we should also expect some anisotropy in the dark energy at large that may be observable specially in the high precision CMB data.

If the dark energy is a cosmological constant the situation is more ambiguous because we don't yet have a generally acceptable definition for a vacuum energy. If its origin is some physics at very high energy scale - Planck or superstring scale - and fixed at very early stage in the evolution of the Universe, the dark energy would be completely static, isotropic, and have no effect other than gravity up to any measurable redshift. In this case an *effective $w < -1$* would be the signature of a non-gravitational interaction in dark matter sector, for instance slow decay of dark matter. If at least part of the remnants of the decay are SM particles, we must be able to observe them as an additional component in cosmic rays. Their energy range depends on the mass of the decaying dark matter particles and can be $E \gtrsim 10^{13}$ GeV or $E \lesssim 100$ GeV. Moreover, it must somehow correlate with the large structures. By contrast, if the remnants are all dark, then they can be only detected through their effect on the structure formation. But this can be very small and very difficult to observe.

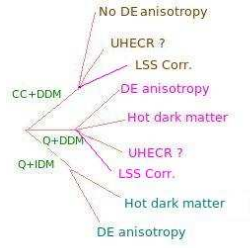The last case we consider here is when the dark energy is the result of the condensation

FIGURE 2. Dark energy models with effective $w < -1$ and their observables.

of a light scalar produced during the decay of a meta-stable dark matter. It has been shown that the equation of state of the condensate is very similar to a cosmological constant [5]. This model can produce a light hot dark matter - the scalar particles - an excess of visible cosmic rays, and/or dark remnants. The anisotropy of the dark energy would be very small but worth to be searched for.

Fig.2 summarizes the possible origins of a dark energy with effective $w < -1$ considered here and their observables.

Evidently, the most important question is how we can observe the tiny and weak interacting observables explained above. In one hand, this needs drastic improvement in the precision of measurements. On the other hand, more precise observations of cosmological effects means more sensitivity to the foreground phenomena that can mislead interpretation of observations. Therefore, the first step in this direction is a better understanding of the foreground. On another front, the discovery of physics beyond the Standard Model by LHC can be very important for clarifying which direction(s), both theoretical and experimental, we should investigate more closely to find the origin of the dark energy.

In conclusion, we have discussed some of the possible models for dark energy with effective $w < -1$ and without violation of the null energy condition. At present these types of dark energy are preferred by the data. Without considering any explicit implementation of these models we investigated the difference between their observables and how this can help to pin-down the underlaying model.

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